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EVALUATION OF MULTIPORT SINGLE-FIBER FIBER-OPTIC COUPLERS.(U)

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Technical Report 368

# EVALUATION OF MULTIPORT SINGLE-FIBER FIBER-OPTIC COUPLERS

TA Meador

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Test and Evaluation Report: 1 August to 30 October 1978

Prepared for
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This report evaluates the performance of multiport fiber-optic couplers designed for use with single-fiber cables in data-bus systems. The effort was part of the Fiber-Optic Device Technology Program, the purposes of which are to develop and evaluate the feasibility and practicability of Naval fiber-optic technology.

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# INTRODUCTION

This effort was carried out as part of the Fiber-Optic Device Technology Program, the purposes of which are to develop and evaluate the feasibility and practicability of naval fiber-optic technology. The goal has been to evaluate the performance of multiport fiber-optic couplers designed for use with single-fiber cables in data-bus systems.

Spectronics, Inc., of Richardson, Texas, is under contract to NOSC, San Diego, to manufacture, test, and deliver single-fiber data-bus couplers. Specifications of the couplers are summarized on page 4 and found in greater detail in the statement of work for NOSC contract N66001-77-C-0097. Thirteen couplers have been delivered; three more are forthcoming. The results obtained are to be used to identify further tasks required for coupler development. Such tasks would be carried out under the Fiber-Optic Device Technology and Manufacturing Technology Programs.

# BACKGROUND

Military data-bus technology has been developed to fulfill platform operational requirements for increased maneuverability, survivability, reliability, and maintainability. The fundamental approach is to use a single common transmission path, called a bus, for most signal transfer within an electronic system. Access to the bus is obtained by system equipments through terminals which perform signal conversion, message processing, and traffic monitoring. Terminals obtain access to the bus by means of couplers. A coupler diverts a portion of the signal power present on the bus to the terminal and directs signal power originating at the terminal onto the bus.

Research, development, and operational experience have been combined to codify aircraft data-bus technology resulting in the promulgation of two standards, MIL-STD-1553A and MIL-G-85013. Surface-platform data-bus technology is being developed through the Shipboard Data Multiplex System (SDMS) Program under NAVSEA sponsorship. The aircraft standards and the evolving shipboard system utilize wire-guided communications. On aircraft the use of shielded twisted-pair cable is specified and the SDMS uses coaxial cable.

Wire transmission is vulnerable to disruption by electromagnetic interference from such sources as switching equipment, transmitters, lightning strikes, or a nuclear-event electromagnetic pulse. On the other hand, glass fibers are transmissive only in the optical portion of the electromagnetic spectrum and are insensitive to radiation at lower frequencies. Thus, a system employing fiber-optic technology should enjoy a higher degree of immunity to electromagnetic interference than one utilizing metallic transmission.

Two fundamental configurations are noteworthy in fiber-optic data-bus design.[1,2] One, the serially tapped bus, is based upon the allocation of a dedicated coupler to each

[1] Milton, A.F., and Brown, L.W., Nonreciprocal Access to Multiterminal Optical Data Highways, IEEE/OSA CLEA, Washington, D.C., May 1973

[2] Hudson, M.C., and Thiel, F. L., Applied Optics, 13, 2450, 1974

terminal. Each coupler, analogous to a coaxial tee, is spliced into the data bus near the terminal it serves. As with a similarly constructed wire bus, the end-to-end loss of such a system of cascaded lossy components increases exponentially with the number of couplers. The second configuration, the star or radial-arm bus, uses a single multiport coupler which is shared by and connected directly to all terminals. The multiport coupler represents a single lumped loss which increases linearly with the number of terminals. Thus, a bus of many terminals will have a much lower loss when built with the multiport coupler.

## MULTIPORT COUPLER OPERATION

The multiport coupler accepts optical power from any input terminal connected to it and distributes that power equally among all output terminals. Typically, a multiport coupler consists of a scrambling block and connecting waveguides as shown in figure 1. These parts are assembled and placed in a housing which provides access to the connecting waveguides through connectors to which terminated fiber channels are attached. The channels extend between the coupler and the terminals.

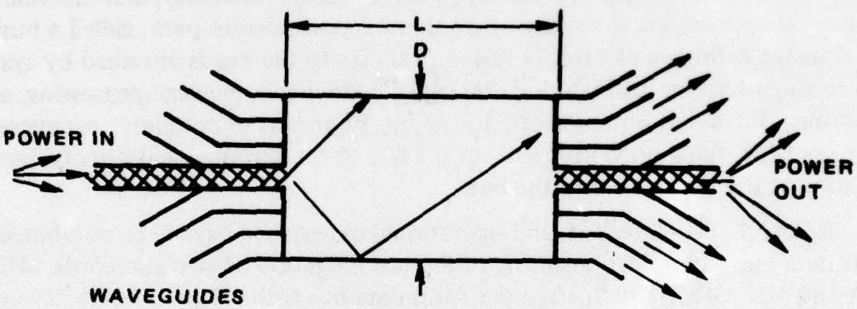


Figure 1. Coupler operation.

Optical power travels through a cable to the coupler where it enters a connecting waveguide. Because of the nature of the optical power source and the fiber-optic bundles, the spatial characteristics of the power entering the waveguide can be approximated by a cone of light. In figure 1 the cone of light leaving any waveguide on the left side of the block spreads across the cross-section of the block and over all the waveguides on the right. The maximum input-cone angle that will experience total internal reflection at the side surface of the block is determined by the refractive index difference at this boundary.

Previous discussions of multiport coupler theory have shown that for efficient operation a coupler must match or exceed the numerical aperture (NA) of the connecting fibers and that the cross-sectional area of the scrambling block must equal the sum of the cross-sectional areas of the connecting fibers. The NAs of the fibers, waveguides, and scrambling block are determined by the difference of the indices of refraction of their core ($N_{core}$) and cladding ($N_{clad}$) materials. In particular, the limiting NA is

$$NA = (N_{core}^2 - N_{clad}^2)^{1/2} . \qquad (1)$$

Light rays which enter a clad optical channel at angles ($\theta$) to the channel axis of up to

$$\theta_{max} = \sin^{-1} (NA) \qquad (2)$$

will be contained within the core.

The optical power entering the scrambling block within $\theta_{max}$ will fan out until reflected at the core/clad interface. In so doing, it will spread over the cross-sectional area of the block which, to conserve power, must equal the sum of the areas of the data-bus fiber channels. Thus, the maximum cross-sectional dimension (D) and minimum length (L) of the optical path in the scrambling block are determinable. Distribution of the optical power over the output ports of a coupler should be uniform to equalize the power levels at all terminals under all transmission conditions. Thus, the length (L) of the mixing block must be adequate. Milton[3] and Biard[4] have reported the necessary relationship between L, D, and NA. Milton[5] has shown that the distributed optical power will vary in intensity over the surface of distribution as an empirical function of $[(L/D)\tan(\theta_{max})]$. Biard[6] has derived an expression for the relationship of L, D, scrambling-block core index, and a specific distribution of input optical power which will result in uniform distribution of the power over the output surface of the block:

$$\frac{L}{D} = \frac{(N^2 - NA^2)^{1/2}}{NA}, \qquad (3)$$

where

L = scrambling-block length
D = scrambling-block cross-sectional dimension
N = scrambling-block index of refraction
NA = numerical aperture of optical power entering the scrambling block.

The significance of this expression is that coupler scrambling-block dimensions and coupler operation are dependent upon the fixed characteristics of the fiber-optic cable with which a coupler is to be used and that employing a given coupler with a different fiber-optic cable may give a different coupler performance.

Performance of a multiport coupler can be specified by the level of optical power available at all output ports relative to the level of input power. Ideally, the only decrease in level should result from power division in the coupler, that is,

$$Po, j = \left(\frac{1}{N}\right) Pi, k, \qquad (4)$$

where

Po, j = power available at output port j
N = number of output ports
Pi, k = power input at port k.

This performance is never attained because factors other than division loss cause attenuation of optical power within the coupler. Chief among these factors are reflections, losses at the core/clad interface, and cross-sectional area misalignment caused by unavoidable mechanical tolerances. Multiport coupler performance can be described by the following:

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[3]Milton, A.F., and Lee, A.B., Applied Optics, 15, 244, 1976

[4]Biard, J.R., and Shaunfield, J.E., Optical Couplers, AFAL-TR-74-314, December 1974

[5]Milton, op. cit., p. 248

[6]Biard, op. cit., p. 71

$$T = \frac{(Po, j)k}{Pi, k} \quad \text{transmission between any two ports} \qquad (5A)$$

$$T^* = \frac{\Sigma(Po, j)k}{Pi, k} \quad \text{total transmission of the coupler} \qquad (5B)$$

$$V = \frac{(Po, j)k}{(Po, j)\ell} \quad \text{port-to-port transmission variation,} \qquad (5C)$$

where

$(Po, j)k$ = power exiting any port j with power input at any other port k

$Pi, k$ = power input at port k

$\Sigma(Po, j)k$ = power exiting all ports save input port k

$\frac{(Po, j)k}{(Po, j)\ell}$ = ratio of output power at any one port j with power input at port k to power output at port j with power input at port $\ell$

These ratios provide a means of specifying device performance. They also enable one to compare diverse coupler designs.

## COUPLER PROCUREMENT AND TESTING

For the purposes of procurement and testing, fiber-optic coupler and cable characteristics were specified as follows:

**Coupler Specifications**

1. Coupler shall interface with
   - Step index fibers
   - Fiber numerical aperture ⩾ 0.18
   - Fiber outer diameter ⩽ 125 μm
   - Fiber core diameter = 100 μm
2. Insertion loss ⩽ 6 dB
3. Deliverables
   - 4 2-port couplers
   - 4 4-port couplers
   - 4 8-port couplers
   - 4 16-port couplers
4. Test cables
   - Conduction cable: step index, 85-μm core, 125-μm fiber, 10-dB/km loss
   - Pickup cable 1: step index, 100-μm core, 150-μm fiber, 50-dB/km loss
   - Pickup cable 2: step index, 200-μm core, 300-μm fiber, 50-dB/km loss

The coupler types are shown in figure 2.

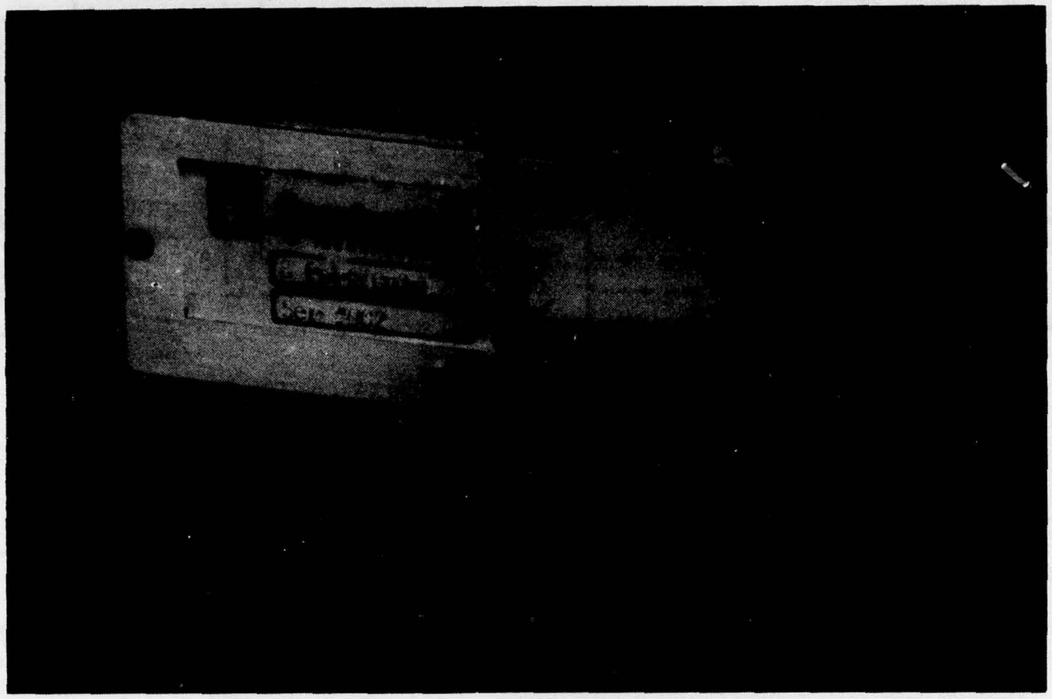

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Figure 2. Multiport couplers.

Two single-fiber cables were used to test the couplers: an 85-$\mu$m-core step-index type to conduct power to the coupler and either a 100- or 200-$\mu$m-core step-index type to conduct power from the coupler to the detector. A current-regulated tungsten source was used together with an interference filter and a lensing system to limit the test spectrum, fill the numerical aperture, and flood the optical aperture of the conducting cable. The conducting cable was 35 m in length and laid in 6-in coils. The pickup cables were less than 1 m in length. All cables were terminated in connectors supplied by the contractor. The tests consisted of comparisons between the power level obtained by butting the conduction and pickup fibers in a bulkhead adaptor and the level obtained by connecting the two cables to the connector. Levels were obtained for all conditions of input and output ports of the 4-, 8-, and 16-port couplers. Figure 3 illustrates the test setup.

Testing of each coupler was initiated by connecting the two free ends of the fiber-optic cables through the splice connector which aligned them in a butt joint. Butting the ends established a zero-loss reference. After determination of the zero-loss reference the two ends were disconnected from the splice connector and connected to the coupler to be tested in each of all possible input/output port combinations. The ratio of the reference level to the coupler output, measured at a port, was taken as the coupler transmission factor (T) for the pair of ports involved. The test results are in table 1.

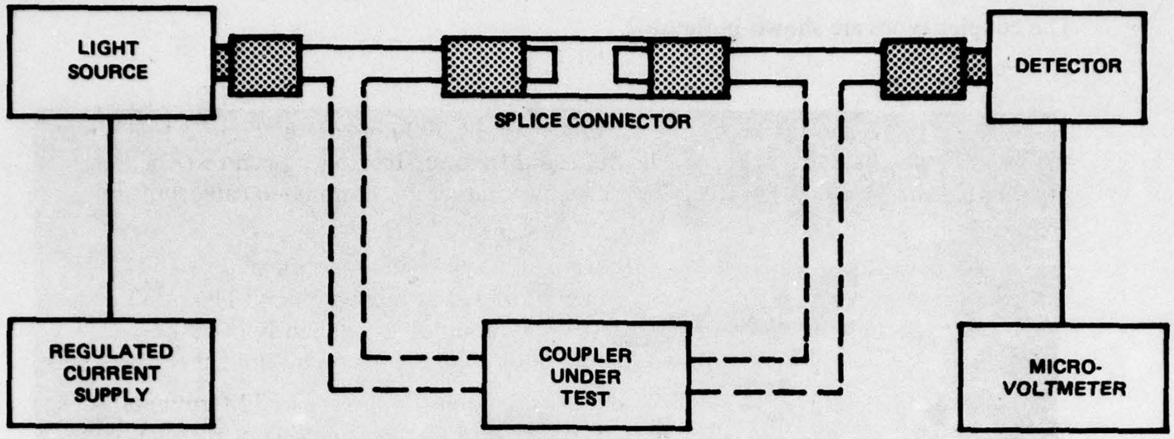


Figure 3. Coupler loss-measuring setup.

Table 1. Summary of measured coupler performance.

| Coupler Serial Number | Number of Ports | Data Source | Average Po/Pi (T) | Average Coupling, 10 $\log_{10}$(T), dB | Average Input Variation, 10 $\log_{10}(V_i)$, dB | Average Output Variation, 10 $\log_{10}(V_o)$, dB |
|---|---|---|---|---|---|---|
| 1 | 4 | C | 0.025 | -16.0 | 2.9 | 3.6 |
| 2 | 4 | C | 0.021 | -16.7 | 2.6 | 2.3 |
| 2 | 4 | NPUP2 | 0.027 | -15.7 | 3.0 | 3.0 |
| 3 | 4 | C | 0.047 | -13.2 | 1.2 | 1.0 |
| 3 | 4 | NPUP2 | 0.05 | -13.0 | 0.7 | 0.6 |
| 4 | 4 | C | 0.039 | -14.1 | 1.0 | 0.9 |
| 4 | 4 | NPUP2 | 0.035 | -14.5 | 2.1 | 2.0 |
| 1 | 8 | C | 0.016 | -17.9 | 3.3 | 3.4 |
| 1 | 8 | NPUP1 | 0.019 | -17.1 | 3.9 | 3.7 |
| 1 | 8 | NPUP2 | 0.017 | -17.7 | 3.8 | 3.8 |
| 3 | 8 | C | 0.019 | -17.2 | 4.2 | 4.3 |
| 3 | 8 | NPUP1 | 0.022 | -16.5 | 4.1 | 4.8 |
| 3 | 8 | NPUP2 | 0.024 | -16.2 | 4.0 | 4.2 |
| 4 | 8 | NPUP2 | 0.014 | -18.4 | 3.4 | 3.5 |
| 1 | 16 | NPUP2 | 0.015 | -18.2 | 7.7 | 7.8 |

In table 1, the column "data source" indicates whether the data were taken by the contractor (C), by NOSC through pickup cable 1 (NPUP1), or by NOSC through pickup cable 2 (NPUP2). The average ratio of power conducted through the butted transmission cables to that level conducted through the assembled cables and coupler is found in the column "average Po/Pi"; the ratio is expressed in decibels in the next column to the right. The average variation of power conducted from the output ports with power conducted into a fixed input port is found in the "average input variation" column, and the ratio of power variation at a given output port resulting from a change in input ports is found in the last column on the right. Each performance parameter in table 1 represents the average for the coupler under test.

The test results show the variability which can be expected in the performance of systems utilizing even a few connectors. When the conduction and pickup cables were interfaced on the first test step, connector rotation could vary the sensed power level by up to 5% with the 100-$\mu$m-core pickup and 1 to 2% with the 200-$\mu$m-core pickup. A buildup of this rotational variation was noted when the couplers were inserted. Each test reading represented the peak transmission achievable by rotating the terminated cable ends in the connectors.

All couplers in hand are of the transmission type and are fabricated by stacking 1 X 2 or 1 X 4 arrays of fibers against both ends of a glass mixing block. The other ends of the fibers are terminated in connector bodies and mounted permanently in bulkhead adaptors which are attached to the coupler bodies. Figure 1 shows assembled connectors.

Since the couplers are transmission type, a 16-port coupler has 32 terminated fibers accessed through bulkhead adaptors; 16 fibers are mounted on one side of the mixing block and 16 fibers are on the other side. Sixteen data-bus terminals would be connected to a 16-port coupler through 16 pairs of fibers, each fiber of the pair leading to opposite sides of the mixing block. One fiber would be utilized for transmission, the other for reception. The results in table 1 are representative of coupler operation in both directions; no significant directionality in coupler operation was noted.

Performance of these couplers is determined by their design. The fibers are attached to the mixing block in square arrays which imposes a packing fraction loss ($\pi/4$) on light exiting through either face. In addition, a core/cladding loss, a dimensional tolerance loss, and a number of reflection losses all contribute to the fundamental coupler inefficiency. Coupler performance is also affected by performance of the connectors through which external fibers are attached to the coupler. The contractor reports that typical loss for his connector is less than 2.0 dB. Given these figures and the fundamental loss of the coupler and adding 10% reduction in transmission for any other absorption-, scattering-, or assembly-caused losses, each coupler should exhibit an insertion loss of approximately 6.8 dB. Coupler loss factors are summarized below:

Coupler Loss Mechanisms (dB)

| | |
|---|---|
| Packing fraction | 1.0 |
| Core/clad | 0.6 |
| Dimension tolerance | 0.6 |
| Reflections | 0.2 |
| Two connectors | 4.0 |
| Excess losses | 0.4 |
| | 6.8 |

When the power division factors are accounted for, the predicted loss for 4-port couplers is −12.8 dB; for 8-port couplers, −15.8 dB; and for 16-port couplers, −18.8 dB. As the 16-port coupler was received last, the contractor's production techniques have obviously improved. The difficulty of handling large numbers of fibers in the manufacturing process is apparent, however, in the differences in port-to-port variation measurements between the 16-port coupler and the other devices. Four ports out of the 32 attached to the coupler exhibited very poor performance and greatly affected the uniformity of power division exhibited by the coupler. These predicted loss figures should be compared with the T values in table 1 by adding another connector loss (2 dB) to the values in the table, since the test method eliminates one connector loss.